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Game Engineering A Multiagent Systems Perspective

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Final Report

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AFOSR Project Final Summary
Jason R. Marden

Contract/Grant Title: Game Engineering A Multiagent Systems Perspective

Contract/Grant #: FA9550-12-1-0359

Reporting Period: 1 July 2012 to 30 June 2015

Awards this Period: 1 July 2014 to 30 June 2015

- 2015: Office of Naval Research Young Investigator Award
- 2015: Best SICON/CST Best SIAM Paper Prize for paper "Achieving Pareto Optimality Through Distributed Learning," SIAM Journal on Control and Optimization, 2014. This work was completed under this proposal.

Top Three Accomplishments During Entire Proposal:

(i) A central component of a game theoretic design is the assignment of objective functions to the individual agents. The following paper proves that generalized weighted Shapley values fully characterize all objective design methodologies that guarantee the existence of a pure Nash equilibrium in resource allocation problems with separable system level objective functions. This result identifies the computational complexity associated with objective design since computing a weighted Shapley value is frequently intractable.

R. Gopalakrishnan, J.R. Marden, and A. Wierman, "Potential Games are Necessary to Ensure Pure Nash Equilibria in Cost Sharing Games," Mathematics of Operations Research, Volume 39, Number 4, pp. 1252-1296, 2014.

(ii) The goal in networked control of multiagent systems is to derive desirable collective behavior through the design of local control algorithms. Undoubtedly, informational restrictions to the agents impose constraints on achievable performance guarantees. One of the most significant accomplishments from this period is a characterization of one such constraint with regards to the efficiency of the resulting stable solutions for a class of networked resource allocation problems with submodular objective functions. This characterization is given in the following paper:

J.R. Marden, "The Role of Information in Distributed Resource Allocation," IEEE Transactions on Control of Networked Systems, 2015 (under review).

(iii) The vast majority of the literature in distributed learning focuses on attaining convergence to Nash equilibria. However, it is widely known that Nash equilibria are often extremely inefficient from a system-wide perspective. Correlated equilibria, on the other hand, can often characterize collective behavior that is far more efficient than even the best Nash equilibrium. However, previously there were no

distributed learning algorithms in the existing literature that provide convergence to specific correlated equilibria. The following paper was the first at establishing distributed learning rules that converge in probability to the most efficient correlated equilibrium.

J.R. Marden, "Selecting Efficient Correlated Equilibria Through Distributed Learning," *Games and Economic Behavior*, 2015 (under review).

Survey of Accomplishments During Entire Proposal:

This project focused on the derivation/analysis of distributed learning algorithms for attaining desirable system-wide behavior in multiagent systems. A summary of the main directions and contributions resulting from this work completed under this proposal are summarized below:

(i) Performance Tradeoffs In Networked Control System with Informational Constraints: The goal in networked control of multiagent systems is to derive desirable collective behavior through the design of local control algorithms. As highlighted above, informational restrictions impose constraints on achievable performance guarantees. One of the most significant accomplishments from this period is a characterization of one such constraint with regards to the efficiency of the resulting stable solutions for a class of networked resource allocation problems with submodular objective functions. When the agents have full information regarding the mission space, the efficiency of the resulting stable solutions is guaranteed to be within 50% of optimal. However, when the agents have only localized information about the mission space, which is a common feature of many well-studied control designs, the efficiency of the resulting stable solutions can be $1/n$ of optimal, where n is the number of agents. Consequently, in general such schemes cannot guarantee that systems comprised of n agents can perform any better than a system comprised of a single agent for identical environmental conditions.

The natural question that emerges is what information presented to the agents could be exploited to overcome such efficiency guarantees. In the context of the well-studied sensor coverage problem, this work identifies how limited aggregate information regarding the environment can overcome such efficiency guarantees. In particular, when the sensors only have a localized view of the mission space, the achievable performance guarantee is $(1/n)$ of optimal. However, if each sensor also has access to the "search value associated with the worst performing sensor" and "the general direction of the worst performing sensor", control algorithms can then be designed that guarantee a performance that is within $(1/2)$ of optimal. While the derived results fall within the context of the well-studied sensor coverage problem, the general guidelines should be extendable to broader settings as well.

Further, new results also highlighted an inherent tradeoff between desirable long-term efficiency guarantees and the resulting convergence rates in multiagent systems.

See publications [J2, C1, C2, C5].

(ii) **Attaining Efficient *Correlated Behavior* Though Distributed Learning:** The vast majority of the literature in distributed learning focuses on attaining convergence to Nash equilibria. However, it is widely known that Nash equilibria are often extremely inefficient from a system-wide perspective. Correlated equilibria, on the other hand, can often characterize collective behavior that is far more efficient than even the best Nash equilibrium. However, previously there were no distributed learning algorithms in the existing literature that provide convergence to specific correlated equilibria. In this activity, we provide two such algorithms. The first algorithm ensures that the behavior of the agents can be characterized by deterministic cycles, which have an empirical frequency that is aligned with the most efficient correlated equilibrium. The second algorithm we propose in this activity guarantees that the agents' collective joint strategy will constitute an efficient correlated equilibrium with high probability. The key to attaining this second algorithm involved incorporating a common random signal into the learning environment.

The results highlighted in the previous progress report focused on ensuring that the empirical frequency of play was aligned with the most efficient (coarse) correlated equilibrium. The results derived this period extended such results to ensure that the day-to-day collective play was consistent with the most efficient coarse correlated equilibria. Here, such randomness in day-to-day joint policies is essential for ensuring desirable performance in team scenarios relevant to the Department of Defense, e.g., team versus team zero sum games. A key novelty here is the introduction of a common random signal into the learning environment that is exploited to attain randomized

See publications [J2, C1, C2, C5].

(iii) **Characterizing the Impact of Adversarial Interventions in Multiagent Coordination:** In a multi-agent system, transitioning from a centralized to a distributed decision-making strategy can introduce vulnerability to adversarial manipulation. In this work, we studied the potential for adversarial manipulation in a class of graphical coordination games where the adversary can pose as a friendly agent in the game, thereby directly influencing the decision-making rules of a subset of agents. The adversary's influence can cascade throughout the system, indirectly influencing other agents' behavior and significantly impacting the emergent collective behavior. These preliminary results focused on characterizing conditions by which the adversary's local influence can dramatically impact the emergent global behavior, e.g., destabilize efficient equilibria. Furthermore, preliminary results demonstrate empirically that safeguarding a multiagent system against adversarial interventions comes at the expense of degrading the responsiveness in the multiagent system, e.g., convergence rates.

See publications [C3].

(iv) **Robust Mechanisms for Social Influence:** Uninfluenced social systems often exhibit suboptimal performance; a common mitigation technique is to charge agents specially-designed taxes, influencing the agents' choices and thereby bringing aggregate social behavior closer to optimal. In general, the efficiency guaranteed by a particular taxation/influencing methodology is limited both by the quality of information available to the system-designer and the sophistication of the available taxation methodologies. If the tax-designer possesses a perfect characterization of the system, it is often straightforward to design taxes that perfectly align agents' incentives with the designer's global objective. However, as the quality of the designer's information decreases, increasingly sophisticated methodologies are required to achieve the same efficiency target.

In this direction, we offer a preliminary study on the role of robust taxation mechanism to influence behavior in a class of routing problem. More specifically, we study the application of taxes to a network-routing game, and we assume that the tax-designer knows neither the network topology nor the tax-sensitivities and demands of the agents. We show that it is possible to design taxes that guarantee that selfish network flows are arbitrarily close to optimal flows, despite the fact that agents' tax-sensitivities are unknown to us. We term these taxes "universal," since they enforce optimal behavior in any routing game without a priori knowledge of the specific game parameters. In general, these taxes may be arbitrarily high; accordingly, for affine cost parallel-network routing games, we explicitly derive the optimal bounded tolls and the best-possible efficiency guarantee as a function of a toll upper-bound. Finally, we restrict attention to very simple fixed-toll methodologies and show that they are incapable of providing strong efficiency guarantees if the designer lacks good information about either the network topology or the user sensitivities.

Extending such results to the domain of human-agent cooperative systems is an ongoing research focus.

See publications [J6, C9].

(v) **Methodologies for Utility Design in Distributed Engineering Systems:** A central component of a game theoretic design is the assignment of objective functions to the individual agents. The design/influence of agent objective functions for social systems has been studied extensively in the game theoretic literature, e.g., cost sharing problems and mechanism design; however the difference between the constraints and objectives pertaining to social and engineering systems requires looking at this literature from a new perspective.

The core objective in engineering systems is to establish a dynamical process that converges to an efficient outcome. Accordingly, there are several competing objectives that a system designer needs to consider when contemplating the underlying design including the locality of the agents' objective functions, the structure of the resulting game, the existence and efficiency of equilibria, among many more. Here, our results focused on the development of such methodologies

for meeting the above objectives. A notable result from this section, in [J7], proves that generalized weighted Shapley values fully characterize all objective design methodologies that guarantee the existence of a pure Nash equilibrium in resource allocation problems with separable system level objective functions. This result identifies the computational complexity associated with objective design since computing a weighted Shapley value is frequently intractable.

A fundamental problem that arises in distributed systems is efficiency loss. That is, the system level performance associated with stable solutions could potentially be much worse than the optimal system level performance. Characterizing efficiency bounds is essential for providing performance guarantees on the system behavior; however, establishing such bounds is fundamentally challenging as evidenced by the lack of such results in the existing literature in distributed control. An opportunity for characterizing such bounds is to leverage off of the significant body of research in the field of algorithmic game theory devoted to analyzing the inefficiency of Nash equilibrium in distributed systems, c.f., price of anarchy. Most of the literature regarding price of anarchy is purely analytical with no design component; hence, its applicability to engineering systems is somewhat limited in its current state. Establishing a methodology that guarantees the existence of a pure Nash equilibrium in addition to optimizing the price of anarchy would have profound implications for multiagent coordination in both social and engineering systems by improving the operational efficiency of such systems. The characterization highlighted above identifies all methodologies that guarantee the existence on a pure Nash equilibrium; hence, this result characterizes the complete design space that a system designer needs to consider when the goal is to optimize the price of anarchy. Furthermore, preliminary results in derive such “optimal” agents’ objective functions for specific problem instantiations, e.g., network coding and submodular resource allocation problems. Ongoing work is seeking to identify more “universal” methodologies for optimizing the price of anarchy in distributed engineering systems.

See publications [J5,J7,C7].

Personnel

Faculty

Jason R. Marden, University of Colorado

Postdocs

Ragavendran Gopalikrishnan
Vinod Ramaswamy

Doctoral Students

Yassmin Shalaby (Graduated with MS, 2014)

Matthew Philips (Graduated with MS, 2015)
Holly Borowski (Will Graduate with PhD, 2016)

Archival Journal Articles Taken from 2014-2015 (this period)

[J1] H. Borowski, J.R. Marden, and J.S. Shamma, "Learning Efficient Correlated Equilibrium," IEEE Transactions on Systems and Cybernetics, 2015 (under review).

[J2] J.R. Marden, "The Role of Information in Distributed Resource Allocation," IEEE Transactions on Control of Networked Systems, 2015 (under review).

[J3]. J.R. Marden, "Selecting Efficient Correlated Equilibria Through Distributed Learning," Games and Economic Behavior, 2015 (under review).

[J4]. H. Borowski and J.R. Marden, "Fast Convergence in Semi-Anonymous Potential Games," IEEE Transactions on Control of Networked Systems, 2015 (to appear).

[J5] J.R. Marden and J.S. Shamma, "Game Theory and Distributed Control," Handbook of Game Theory, Volume IV, edited by Peyton Young and Shmuel Zamir, Elsevier Science, 2014.

[J6] P.N. Brown and J.R. Marden, "Robust Taxation Mechanisms in Affine Congestion Games with Price-Sensitive Users," IEEE Transactions on Automatic Control, 2015 (under review).

[J7] R. Gopalakrishnan, J.R. Marden, and A. Wierman, "Potential Games are Necessary to Ensure Pure Nash Equilibria in Cost Sharing Games," Mathematics of Operations Research, Volume 39, Number 4, pp. 1252-1296, 2014.

Conference Papers (this period)

[C1] V. Ramaswamy and J.R. Marden, "A Sensor Coverage Game with Improved Efficiency Guarantees," American Control Conference, 2016 (under review).

[C2] J.R. Marden, B. Touri, R. Gopalakrishnan, and J.P. O'Brien, "The impact of information in a simple multiagent collaborative task," IEEE Conference on Decision and Control, 2015.

[C3] H. Borowski and J.R. Marden, "Understanding the Influence of Adversaries in Distributed Systems," IEEE Conference on Decision and Control, 2015.

[C4] J.R. Marden, "Selecting Efficient Correlated Equilibria Through Distributed Learning," American Control Conference, 2015.

[C5] J.R. Marden, "The Role of Information in Multiagent Coordination," IEEE Conference on Decision and Control, 2014.

- [C6] H. Borowski, J.R. Marden, and J.S. Shamma, "Learning Efficient Correlated Equilibria," IEEE Conference on Decision and Control, 2014.
- [C7] R. Gopalakrishnan, S. Nixon, J.R. Marden, "Stable Utility Design for Distributed Resource Allocation," IEEE Conference on Decision and Control, 2014.
- [C8] H. Borowski and J.R. Marden, "Fast Convergence for Time-Varying Semi-Anonymous Potential Games," American Control Conference, 2014.
- [C9] P.N. Brown and J.R. Marden, "Optimal Mechanisms for Robust Coordination in Congestion Games," IEEE Conference on Decision and Control, 2015.

Cumulative List of Journal Publications:

- [1] H. Borowski, J.R. Marden, and J.S. Shamma, "Learning Efficient Correlated Equilibrium," IEEE Transactions on Systems and Cybernetics, 2015 (under review).
- [2] J.R. Marden, "The Role of Information in Distributed Resource Allocation," IEEE Transactions on Control of Networked Systems, 2015 (under review).
- [3] J.R. Marden, "Selecting Efficient Correlated Equilibria Through Distributed Learning," Games and Economic Behavior, 2015 (under review).
- [4] H. Borowski and J.R. Marden, "Fast Convergence in Semi-Anonymous Potential Games," IEEE Transactions on Control of Networked Systems, 2015 (to appear).
- [5] J.R. Marden and J.S. Shamma, "Game Theory and Distributed Control," Handbook of Game Theory, Volume IV, edited by Peyton Young and Shmuel Zamir, Elsevier Science, 2014.
- [6] P.N. Brown and J.R. Marden, "Robust Taxation Mechanisms in Affine Congestion Games with Price-Sensitive Users," IEEE Transactions on Automatic Control, 2015 (under review).
- [7] R. Gopalakrishnan, J.R. Marden, and A. Wierman, "Potential Games are Necessary to Ensure Pure Nash Equilibria in Cost Sharing Games," Mathematics of Operations Research, Volume 39, Number 4, pp. 1252-1296, 2014.
- [8] J.R. Marden, H.P. Young, and L.Y. Pao, "Achieving Pareto Optimality Through Distributed Learning," SIAM Journal on Control and Optimization, Volume 52, Issue 2, pp. 2753-2770, 2014. **[SIAM/CST Best Sicon Paper Prize]**
- [9] N. Li and J.R. Marden, "Decoupling Coupled Constraints Through Utility Design," IEEE Transactions on Automatic Control, Volume 59, Issue 8, 2014.
- [10] J.R. Marden and T. Roughgarden, "Generalized Efficiency Bounds in Distributed

Resource Allocation," IEEE Transactions on Automatic Control, Volume 59, Number 3, 2014.

[11] N. Li and J.R. Marden, "Game Design for Distributed Optimization," IEEE Journal of Selected Topics in Signal Processing, special issue on Adaptation and Learning over Complex Networks, Volume 7, Number 2, 2013.

[12] J.R. Marden, S. Ruben, and L.Y. Pao, "Model-Free Approach to Wind Farm Control Using Game Theoretic Methods," IEEE Transactions on Control Systems Technology, special issue "to tame the wind: advanced control applications in wind energy," Volume 21, Number 4, pp. 1207-1214, 2013.

[13] J.R. Marden and A. Wierman, "Distributed Welfare Games," Operations Research, Volume 61, Issue 1, pp. 155-168, 2013.

[14] J.R. Marden and A. Wierman, "Overcoming The Limitations of Utility Design for Multiagent Systems," IEEE Transactions on Automatic Control, Volume 58, Number 6, pp. 1402-1415, 2013.

[15] J.R. Marden, "State Based Potential Games," Automatica, 2012.

Changes in research objectives: None

Changes in AFOSR program manager: Transition from Fariba Fahroo to Frederick Leve, 2015.

Extension granted or milestones slipped: None

New discoveries, inventions, or patent disclosures: None

1.

1. Report Type

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Jason Marden

Program Manager**The AFOSR Program Manager currently assigned to the award**

Frederick Leve

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07/01/2012

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06/30/2015

Abstract

A central goal for the field of distributed control is to develop an underlying theory for the design and control of multiagent systems. Achieving this goal is fundamentally challenging stemming from the underlying complexity associated with a potentially large number of interacting agents and the analytical difficulties of dealing with overlapping and partial information. Game theory is beginning to emerge as a promising new direction for achieving this goal. The reason for this emergence is the similarity between the prevalent decision making architecture in social systems and the desired decision making architecture in distributed engineering systems. Accordingly, many existing game theoretic tools for analyzing behavior in social systems are immediately accessible as design tools for prescribing desirable behavior in distributed engineering systems. The applicability of game theoretic tools for this new prescriptive agenda has led to significant breakthroughs in the analysis and design of multiagent systems; however, the broader research effort connecting game theory to distributed control has ultimately fallen short of providing a systematic design methodology for multiagent coordination. The proposed research effort will address these deficiencies through the development of "game engineering" methodologies using an improved game theoretic framework that is better suited to handle the challenges inherent to multiagent coordination. These developments will formally advance the role of game theory in distributed control and will promote the development of systematic design methodologies for multiagent coordination in both social and

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[J1] H. Borowski, J.R. Marden, and J.S. Shamma, "Learning Efficient Correlated Equilibrium," IEEE Transactions on Systems and Cybernetics, 2015 (under review).

[J2] J.R. Marden, "The Role of Information in Distributed Resource Allocation," IEEE Transactions on Control of Networked Systems, 2015 (under review).

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2. New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

N/A

Change in AFOSR Program Manager, if any:

N/A

Extensions granted or milestones slipped, if any:

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LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, \$K)

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